DOCTORAL THESIS IN THEORETICAL PHYSICS

Quantum Cosmology:

An Epistemological and Ontological Perspective

on Quantum Cosmology, the Levels of the Multiverse, and the MWI = Cosmological Multiverse Hypothesis

Towards a Structural Unification of the Many-Worlds Interpretation, Loop Quantum Gravity, and M-Theory

Quantum Cosmology · Quantum Gravity · Foundations of Quantum Mechanics

Working Draft |

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Chapter 1: Introduction

This thesis argues that the many-worlds interpretation of quantum mechanics is unable to derive objective probabilities and the Born rule without falling into circular arguments, and that current cosmological models — such as inflationary or cyclic models — offer an epistemologically incomplete view of reality, each presenting its own problems, failing to incorporate quantum gravity and generating the emergence of infinities when the block universe hypothesis breaks down.

However, with a quantum cosmology model, and with a universal wavefunction incorporating a closed timelike curve (CTC), and applying the Everett interpretation, all these problems dissolve, offering a complete, objective, and ontological view of the universe, giving rise to a spatially finite, edgeless, and seemingly static block universe model, which provides ontological insight into the meaning of the arrow of time and probabilities within the framework of quantum mechanics.

Furthermore, the model combines with current theories that attempt to solve the problem of quantum gravity, prioritising a type of discrete space-time. This 'quantum multiverse' model connects with relativistic cosmological models through the Cosmological Multiverse (MWI) hypothesis, applying a holographic method and the principle of complementarity, with both space-time and the Born rule emerging naturally.

A central and previously underexplored dimension of this thesis is the asymmetric structural contribution that MWI can make to the two leading candidates for a quantum theory of gravity: Loop Quantum Gravity (LQG) and M-Theory/String Theory. The thesis argues that MWI is not merely one interpretation among others of equal standing, but the unique mechanism by which time, classical geometry, and quantum probabilities can emerge from a timeless, geometry-free quantum substrate — precisely the derivation that both LQG and M-Theory require but cannot supply from their internal resources alone.

> *Central hypothesis: MWI = Cosmological Multiverse is not a speculative equation but the recognition that the quantum universe (ontological background) and the relativistic-cosmological multiverse (epistemological levels) are the same structure described in two languages. A complete quantum theory of gravity must make this equivalence exact and derivable.*

This thesis further shows that without a theory of hidden variables and superdeterminism, this model is the only way to reconstruct determinism given the measurement problem. If it is not true, then reality is intrinsically indeterminate, and there is no arrow of time without the appearance of infinities. Only a hidden-variable interpretation could represent a model similar to the one presented here, but it would be inevitably superdeterministic and entail a number of problems that show that Bohm's interpretation is a many-worlds-in-denial interpretation.

Furthermore, both in single-universe models and in cyclic or inflationary models, it is shown that Bohm's interpretation is not able to reproduce the existence of a single possible world, even when the initial conditions during the birth of each universe are the same — whether during a big bounce or the birth of bubble universes or 'creation ex nihilo', which is a highly restrictive and unlikely scenario.

Chapter 2: Levels of the Quantum Multiverse: An Epistemological and Ontological Perspective

2.1 Re-evaluating the Multiverse: Beyond Tegmark Classification

The notion of a multiverse — a hypothetical set of multiple universes — has gained considerable attention in theoretical physics and cosmology. Although the idea of parallel universes has been contemplated throughout history, it has only been in recent decades, driven by advances in quantum cosmology and string theory, that the concept has acquired a more scientific framework. Max Tegmark proposed an influential classification of multiverses into four distinct levels, each with an increasing diversity of universes. However, this thesis introduces a novel perspective, presenting a classification of the first three levels of the multiverse as inherently epistemological — related to our way of knowing and observing reality — while the fourth level is conceived as the ontological form of the universe itself.

Quantum cosmology is based on the idea that the principles of quantum mechanics should apply to everything in nature, including the entire universe. This approach attempts to answer open questions in classical physical cosmology, such as those concerning the early stages of the universe. It is important to note, however, that there is still no single, fully defined version of a theory that describes the universe as a quantum system.

The distinction between an epistemological and an ontological view of the multiverse is fundamental. Epistemology concerns the nature and scope of knowledge, the justification of beliefs, and the limits of what we can know. Applied to the multiverse, an epistemological level refers to a perspective or framework within which we understand or access the possibility of other universes, influenced by our observational or interpretive limitations. Ontology, on the other hand, refers to the study of being or existence. An ontological level of the multiverse implies the real and fundamental existence of other universes, independent of our ability to directly observe or know them.

2.2 Epistemological Levels: Perspectives on Reality

The first three epistemological levels of the multiverse represent different ways in which we can conceive or have knowledge of the existence of other universes, influenced by our limitations and theoretical frameworks.

The first epistemological level relates to the regions of spacetime that are currently unobservable due to the expansion of the universe and the finite speed of light. The concept of the Hubble volume, which represents everything currently visible from Earth, illustrates this limitation. If space is infinite, as some observations of the cosmic microwave background suggest, then there must be an infinite number of Hubble volumes, each with potentially different histories, though obeying the same effective laws of physics. This level resembles Tegmark's Level I, the quilted multiverse. The practical impossibility of interacting with or even observing these regions beyond our cosmic horizon defines their epistemological nature: their existence is a logical consequence of our cosmological theories and observations, but they remain outside our direct empirical reach.

The second epistemological level concerns the possibility of universes with different physical constants or even different laws of physics, as suggested by Tegmark's Level II, the inflationary

multiverse. The theory of eternal inflation postulates that during the early inflationary phase of the universe, some regions of space stopped expanding and formed 'bubble universes', while other regions continued to inflate. These different bubble universes might have undergone different symmetry breaking, leading to different sets of elementary particles, physical constants, and spacetime dimensionality. Our understanding of these universes is based on theoretical models and extrapolations of our own physical laws. The impossibility of travelling to or even observing these other bubble universes, due to the continuing inflation of the space between them, places them on an epistemological level.

The third epistemological level arises from the different interpretations of quantum mechanics, particularly the many-worlds interpretation (MWI). According to the MWI, whenever a quantum event occurs, the universe splits into multiple branches, each representing one of the possible outcomes. These branches or parallel worlds coexist, but do not interact with each other due to the decoherence phenomenon. From an epistemological perspective, the MWI offers a way to understand the probabilistic nature of quantum mechanics without resorting to the wavefunction collapse postulate. This level corresponds to Tegmark's Level III, the quantum multiverse, and represents a problem of redundant universes in which the parallel universes of MWI are identical to the universes of Levels I and II, but independent of each other.

2.3 The Ontological Level: The Fundamental Nature of Existence

The fourth level of the multiverse is fundamentally quantum and represents the ontological form of the universe. Unlike the previous epistemological levels, which focus on our way of knowing or interpreting reality, this level refers to the fundamental existence of all possible universes arising from a single universal wave function, regardless of our ability to observe or understand them. The possibility of discrete spacetime — a concept that has arisen in various quantum gravity theories such as loop quantum gravity and string theory — is a possible component of this ontological level.

The idea of a discrete space-time suggests that at very small scales, space and time are not continuous, but are composed of indivisible fundamental units. In loop quantum gravity, for example, space-time is considered to be composed of a finite network of entangled loops called spin lattices, whose time evolution gives rise to spin foams. String theory also involves a fundamental scale, the Planck length, where conventional notions of space and time might cease to hold. A model of quantum cosmology with discrete space-time could provide an ontological basis for the multiverse, where different universes correspond to different configurations or states of these discrete fundamental units.

This ontological level could be related to Tegmark's Level IV, the mathematical universe, which postulates that every consistent mathematical structure also exists physically. The key distinction, however, is that unlike Tegmark's model — which is unclear as to whether his Level IV is an ontological or epistemological view — at Level IV of the present model, the entire universe is ontologically a universal wavefunction, with Levels I and II actually being the same as Level III (MWI = Cosmological Multiverse), imposing limits on the redundancy of universes while removing the limitations and problems posed by cosmological models and the Everett interpretation alone.

2.4 Contrasting Perspectives: Comparison with Tegmark's Multiverse

Level	Proposed Model (Epistemological/Ontological)	Tegmark Model	Key Differences
1	Unobservable Regions (Epistemological)	Level I: Quilted Multiverse	Emphasis on observational limitation as the basis for classification.
2	Universes with Different Physical Constants (Epistemological)	Level II: Inflationary Multiverse	Considered a limitation in our knowledge of possible physical laws.
3	Quantum Interpretations (Epistemological)	Level III: Many Worlds Interpretation	Classified as a limited and subjective perspective; 'Cosmological Multiverse + MWI = redundantly infinite multiverse.'
4	Discrete Space-Time (Ontological)	Level IV: Mathematical Universe	Specifies a fundamental basis (discrete spacetime); at this level MWI = Cosmological Multiverse, eliminating redundancy.

Chapter 3: The Redundancy Problem and the Case for a Quantum-Gravitational Resolution

3.1 Anatomy of the Problem

Contemporary theoretical physics faces an unprecedented proliferation of multiverses. Each cutting-edge theory seems to generate, as an almost inevitable by-product, a multiplicity of universes. This phenomenon is not accidental: it is the manifestation of a deep structural tension between the quantum formalism and classical-relativistic cosmological models.

The principal generators of multiverses are:

- MWI (Tegmark Level III): every quantum event branches the universe into multiple branches. The number of branches grows exponentially with each interaction. In the cosmological limit, the wave function of the universe simultaneously contains all possible histories.
- Eternal Inflation (Level II): the inflaton field generates regions of false vacuum that never stop inflating, nucleating bubble universes with different physical constants and broken symmetry groups. The number of bubble universes is potentially infinite.
- Cyclic Models (ekpyrotic, LQC with Big Bounce): the universe collapses and bounces indefinitely. Each cycle constitutes in principle a separate universe with different initial conditions — quantum genesis of universes ex nihilo.
- String Landscape (approximate Level IV): M-Theory admits an estimated 10^500 distinct stable vacua, each corresponding to a universe with different low-energy physics.

The problem is not the existence of multiple universes per se, but the redundancy: MWI produces the same universe as Tegmark's Level I (causally disconnected regions), the same as Level II (universes with different constants), and both produce the same multiverse as the string landscape. These are four descriptions of the same object formulated in mutually incompatible languages.

> *Formal problem: if MWI and eternal inflation generate the same set of universes — all those consistent with the laws of physics — then the final theory must either derive one from the other or show that they are dual. The absence of this bridge is the central epistemological crisis of current quantum cosmology.*

3.2 Why the Redundancy Requires a Quantum-Gravitational Solution

The redundancy cannot be resolved within any of the theories separately. It requires precisely a quantum theory of gravity that operates at the Planck scale and unifies the quantum formalism with the geometry of spacetime. The reasons are as follows:

- MWI operates over Hilbert space without reference to the geometry of spacetime. It cannot discriminate between branches that correspond to different geometries.
- LQG quantises geometry but has no standard quantum interpretation: the preferred basis problem is equivalent to the preferred basis problem of MWI.
- M-Theory has the landscape but no selection principle. The anthropic principle is an epistemic answer, not an ontological one.
- The holographic principle (AdS/CFT) suggests that bulk spacetime emerges from quantum information on the boundary, which implies that MWI branches and bulk geometries are related by duality, not by contingency.

The resolution of this redundancy is therefore not merely a matter of philosophical preference between interpretations but a structural requirement that a complete quantum theory of gravity must fulfil. The thesis argues that MWI uniquely provides the missing emergence mechanism — the process by which time, classical geometry, and quantum probabilities arise from a timeless, geometry-free quantum substrate.

Chapter 4: Fundamental Principles of Quantum Cosmology

4.1 The Quest for Unification: Quantum Mechanics and General Relativity

Quantum cosmology is a branch of theoretical physics whose primary objective is to achieve a unified description of the universe by merging the principles of quantum mechanics and Einstein's theory of general relativity. This endeavour arises from the profound understanding that these two theories — pillars of modern physics — although enormously successful in their respective domains of application, are fundamentally incompatible when applied simultaneously to extreme scenarios, such as the early universe or the interior of black holes.

Quantum mechanics, which describes the behaviour of matter and energy at atomic and subatomic scales, is based on the quantisation of physical properties and the probabilistic nature of phenomena. In contrast, general relativity describes gravity not as a force, but as the curvature of space-time caused by the presence of mass and energy, presenting a deterministic, classical universe on a large scale.

One of the most significant incompatibilities between these theories lies in their treatment of time. In quantum mechanics, time is considered an external classical parameter — an unchanging background against which quantum systems evolve according to the Schrödinger equation. General relativity, on the other hand, integrates time as the fourth dimension of spacetime, a dynamical entity whose flow rate depends on the curvature of spacetime and the trajectory of the observer. This disparity in the conception of time poses a fundamental challenge to any attempt at unification, and is discussed at length in Chapter 7 in the context of MWI's structural contribution to LQG.

Another major obstacle in the search for a quantum theory of gravity is the renormalisation problem. Quantising gravity using standard quantum field theory techniques leads to the emergence of infinities that cannot be removed by renormalisation — a procedure that works successfully for other fundamental forces such as electromagnetism and the weak and strong nuclear forces. This non-renormalisability suggests that general relativity, as currently formulated, might be an effective theory valid only at low energies, and that a more fundamental description at higher energies would require a new theoretical framework.

4.2 Key Concepts and Formalisms in Quantum Cosmology

At the heart of quantum cosmology is the idea of describing the quantum state of the universe by a wavefunction, analogous to the wavefunction of a particle in standard quantum mechanics. Unlike the wavefunction of a particle which evolves in space and time, the wavefunction of the universe is defined in an abstract space of all possible three-dimensional geometries and configurations of matter fields, known as superspace. The equation that this wavefunction is supposed to satisfy is the Wheeler-DeWitt equation — a differential functional equation that arises by applying canonical quantisation procedures to the Hamiltonian formulation of general relativity.

$$\hat{H}\,|\Psi\rangle = 0$$

The Wheeler-DeWitt equation, proposed by John Wheeler and Bryce DeWitt in the 1960s, represents an attempt to quantise gravity by applying the principles of quantum mechanics to the universe as a whole. Unlike the Schrödinger equation, it does not contain an explicit time parameter, reflecting the timeless nature of general relativity at a fundamental level. Instead, it takes the form of a constraint equation, imposing conditions that the wavefunction of the universe must satisfy. The absence of time in this equation is one of the deepest conceptual problems in quantum cosmology, and the mechanism by which time can emerge from it is analysed in detail in Chapter 7.

The concept of superspace is fundamental to the formulation of quantum cosmology. It is an infinite-dimensional space where each point represents a possible three-dimensional geometry of the universe, along with the configuration of all present matter fields. The wave function of the

universe is a functional defined on this superspace, which assigns a probability amplitude to each possible configuration.

In addition to the Wheeler-DeWitt equation, quantum cosmology also explores the importance of boundary conditions for the universe. An influential proposal in this regard is the Hartle-Hawking no-boundary proposal, which suggests that the history of the universe is a compact spacetime manifold with no boundary, analogous to the surface of a sphere. This eliminates the need for an initial singularity and provides a more natural description of the origin of the universe from a quantum state.

4.3 Main Challenges and Open Questions

Despite its ambitious goals, quantum cosmology faces numerous conceptual and technical challenges. The 'time problem' — the absence of an explicit time parameter in the Wheeler-DeWitt equation — makes it difficult to describe the temporal evolution of the universe as we observe it. Several solutions have been proposed, such as identifying an intrinsic variable within the formalism that can act as a clock (the Page-Wootters mechanism), or studying semiclassical evolution where time emerges in an approximate manner. These solutions are analysed in depth in Chapter 7.

Another important challenge is the problem of the Big Bang singularity. Classical cosmology predicts that the universe emerged from a state of infinite density and curvature approximately 13.8 billion years ago. Quantum cosmology offers the hope of resolving this singularity by replacing it with smoother quantum behaviour, such as a 'big bounce' in loop quantum gravity, where a previous contraction phase is followed by an expansion phase.

Interpreting the universe's wave function also presents a significant challenge. Unlike the wave function of a typical quantum system, there is no observer outside the universe who could make measurements and cause the wave function to collapse (if one adheres to the Copenhagen interpretation). This raises questions about how the universe's wave function relates to the classical reality we observe and whether a different interpretation of quantum mechanics is required in a cosmological context — a question to which this thesis argues MWI is the unique satisfactory answer.

Finally, quantum cosmology largely lacks direct experimental verification. The energies involved in the early Universe and at the Planck scale are far beyond what current experiments can probe. However, some researchers hope that quantum effects of gravity may leave subtle imprints on the cosmic microwave background or the large-scale distribution of galaxies, which could be detected with future observations.

Chapter 5: The Many-Worlds Interpretation: The Measurement Problem and Its Structural Role

5.1 The Enigma of Measurement in Quantum Mechanics

One of the most puzzling and debated problems in the foundations of quantum mechanics is the measurement problem. Quantum mechanics describes physical systems by a wavefunction that evolves deterministically according to the Schrödinger equation as a linear superposition of different states. However, when a measurement is performed on a quantum system, it is always found in a single defined state, rather than in a superposition of all possible states. This transition from a superposition to a definite outcome is known as wavefunction collapse, and the measurement problem lies in describing what exactly causes this collapse and how it happens.

The Schrödinger's cat thought experiment vividly illustrates this problem. In this scenario, a cat is enclosed in a box with a device that will release a poison if a radioactive atom decays. According to quantum mechanics, until the box is opened and the system is observed, the atom is in a superposition of decayed and non-decayed states, and therefore the cat is also in a superposition of alive and dead states. However, upon opening the box, we only find the cat alive or dead, never in a combination of both. The question is: how does the system transition from this indefinite superposition to a single definite outcome?

The standard Copenhagen interpretation postulates that measurement plays a special role, causing a non-unitary and irreversible collapse of the quantum state. However, this interpretation has been criticised for its lack of clarity regarding what exactly constitutes a measurement and the role of the observer. The fundamental division between a quantum system and a classical observer appears ad hoc and is not well-defined within the theory.

5.2 The Many-Worlds Interpretation: An Alternative Framework

The many-worlds interpretation (MWI), originally proposed by Hugh Everett III in 1957, offers a radical solution to the measurement problem by suggesting that a collapse of the wavefunction never occurs. Instead, the MWI posits that all possible outcomes of a quantum measurement are physically realised, each on a separate branch of the universe. According to this interpretation, the universe evolves deterministically according to the Schrödinger equation, and the act of measurement is simply an interaction between the quantum system and the measuring apparatus, leading to a superposition state in which all possible histories become real — but in parallel, non-interacting worlds.

The phenomenon of decoherence plays a crucial role in MWI in explaining why we are unaware of these other worlds. Decoherence is the process by which a quantum system interacts with its environment, causing it to lose quantum coherence and behave more classically. In the context of MWI, decoherence causes the universe to branch into distinct worlds that no longer interfere with each other. Each branch contains a defined measurement outcome, and the observer finds himself entangled with one of these branches, perceiving only the corresponding outcome.

The MWI has profound implications for our understanding of reality. It suggests that the universe is not unique, but a vast, constantly branching multiverse where all quantum possibilities play

out. This interpretation eliminates the need for wavefunction collapse and provides a unitary, deterministic description of the quantum evolution of the universe as a whole.

5.3 Challenges and Criticisms of the Many-Worlds Interpretation

Despite its elegance and ability to solve the measurement problem, MWI is not without challenges and criticisms. One of the main objections is the preferred basis problem. MWI postulates a branching of the universe into different worlds, but it does not uniquely specify in which basis this branching occurs. While decoherence helps to select an 'effective' basis for macroscopic objects, it does not provide a preferred fundamental basis at the quantum level.

Another challenge is the difficulty of defining and counting worlds. If every quantum event leads to a split, the number of parallel worlds must be immense, perhaps infinite. Some critics argue that the proliferation of unobservable universes is an ontological extravagance that violates Occam's razor.

A particularly thorny problem for MWI is the derivation of objective probabilities — specifically the Born rule. The Born rule states that the probability of obtaining a particular outcome in a quantum measurement is given by the square of the amplitude of the wavefunction for that outcome. In MWI, where all outcomes occur in different worlds, it is not clear why we should assign probabilities to these outcomes, since they are all true in some world. Several attempts have been proposed, including frequentist arguments, decision-theoretic derivations, self-localising uncertainty, and branch counting — but these remain controversial and have faced criticism for circularity or reliance on additional assumptions.

5.4 From Interpretation to Structural Component: MWI's Unique Role in Quantum Gravity

The challenges described above have traditionally been used to argue that MWI is merely one interpretation among equals. This thesis argues for the opposite conclusion: precisely because MWI begins from a timeless, collapseless universal wave function, it is the only interpretation that is structurally compatible with both the Wheeler-DeWitt equation (which has no time parameter) and the holographic principle (which requires a superposition of boundary states to generate bulk geometries). The remaining chapters of this thesis make this argument specific and technical.

> *The standard objection that MWI cannot derive the Born rule without circularity is here reframed as an opportunity: if the Born rule can be derived from the entanglement structure of the holographic boundary (as the 'It from Qubit' programme suggests), then MWI's apparent weakness becomes the very mechanism that connects it to quantum gravity. The Born rule is not a problem to be solved within MWI but a quantity to be derived from the deeper ontological level (Level 4) through holography.*

Chapter 6: Time and Reality: The Block Universe in Quantum Cosmology

6.1 The Block Universe Concept

Block universe theory, also known as eternalism, presents a radical perspective on the nature of time, suggesting that all moments in time — past, present, and future — exist simultaneously within a four-dimensional block of space-time. In this model, time does not flow objectively, and the universe does not change; rather, all events that have occurred, are occurring, and will occur are equally present within this static block. Our perception of the passage of time and change is considered a psychological illusion, similar to how a movie presents a series of static frames that create the illusion of motion.

This view of time arises naturally from Einstein's theory of special relativity, which treats time as another dimension on an equal footing with the three spatial dimensions, forming a space-time continuum. Special relativity showed that simultaneity is not absolute, but depends on the observer's frame of reference. This relativity of simultaneity suggests that there is no universally defined 'present', supporting the idea that all moments in time have the same ontological status.

The block-universe theory contrasts sharply with other conceptions of time, such as presentism, which holds that only the present moment is real, and growing-block theory, which posits that the past and present exist but the future has not yet materialised. Whereas presentism is more in line with our everyday intuition of time as flowing, the block-universe theory is seen as a natural outgrowth of the theory of relativity.

The preeminence of the block universe as the central conceptual framework in this thesis is based on its intrinsic coherence with a deterministic universe. In contrast, an indeterministic universe presents serious conceptual difficulties. The inherently random nature of its development entails an arbitrariness and bias that make it difficult to define a well-defined beginning or end to the universe — or even both — with the appearance of infinity. In the context of a deterministic universe, concepts such as presentism and the growing block can be interpreted as partial or epistemological views of a more fundamental and complete temporal reality: the block universe.

6.2 Implications for the Nature of Time and Causality

The conception of the universe as a static block has profound implications for our understanding of the nature of time and causality. If all moments exist simultaneously, the notion of the 'passage' of time becomes a puzzle. Some philosophers and physicists suggest that our perception of flowing time is simply a function of our consciousness or of the increasing entropy in the universe, which defines a thermodynamic time direction. From this perspective, the past appears fixed to us because we have memories of it, while the future appears uncertain because we have not yet experienced it. In reality, both exist within the space-time block.

The idea of a block universe also raises questions about free will. If the future already exists, predetermined within the block, do we really have the ability to make choices that alter the course of events? Some argue that free will and determinism can coexist, suggesting that our choices are simply part of the pre-existing structure of the block. Causality in the block universe can be

seen as a web of interconnections across space-time rather than a strictly sequential relationship, and some have even explored the possibility of retrocausality within this framework.

6.3 The Block Universe in Relation to Quantum Cosmology and MWI

The many-worlds interpretation of quantum mechanics seems to fit more naturally with the concept of a block universe than any other interpretation. In the MWI, every quantum event leads to a branching of the universe, creating multiple parallel worlds where all possible outcomes are realised. Within the framework of a block universe, these branches could be viewed as different timelines or histories coexisting within the block spacetime, creating a block 'multiverse' where not only all past, present, and future exist, but also all possible variations of these — resulting in a quantum universe with a closed timelike curve (CTC).

It is interesting to note that Hugh Everett himself, the original proponent of MWI, may not have been entirely in favour of the 'many worlds' terminology, perhaps preferring a view of a single quantum world described by a universal wavefunction within a block universe. From this perspective, the different 'branches' of the wavefunction might not represent separate universes, but rather different components of a single universal quantum state coexisting within the block of space-time. Decoherence would explain why these components appear classical and do not interact at the macroscopic level.

> *The combination of block universe + MWI + CTC yields a universe that is finite, edgeless, and apparently static from an external (ontological) point of view, but that contains an emergent arrow of time in each branch from an internal (epistemological) point of view. This structure reconciles the relativistic block universe with the irreversible quantum dynamics observed at every scale.*

Chapter 7: MWI as Structural Bridge for Loop Quantum Gravity: Deriving Time and the Arrow of Time

7.1 The Problem of Time in LQG: Technical Diagnosis

The problem of time is universally recognised as the deepest obstacle in Loop Quantum Gravity and in quantum cosmology generally. Its nature is simultaneously technical and philosophical, and no other interpretation of quantum mechanics has offered a structural — as opposed to merely verbal — solution to it.

In the canonical formalism of LQG, the central equation is the Wheeler-DeWitt equation in its discrete version. This equation imposes that the total Hamiltonian operator applied to the wave function of the universe gives zero. There is no explicit time parameter. The universe, described in its totality, is a static object in superspace. There is no temporal evolution in the conventional sense.

The consequences are devastating for observable physics:

- There is no way to define 'before' and 'after' at a fundamental level. Causality is an emergent property that LQG cannot derive from its basic equations.
- The arrow of time — the fact that entropy grows in one direction — has no correlate in the Wheeler-DeWitt equation. Thermodynamic time is external to the formalism.
- Classical General Relativity must emerge as a semiclassical limit, but the mechanism by which a timeless equation generates a dynamic geometry with a well-defined time is obscure.
- Attempts to introduce an internal reference time (relational or York time) are ad hoc and do not resolve the problem in the deep quantum regime.

7.2 Why MWI is the Only Interpretation That Can Structurally Resolve the Problem of Time

This section makes the central structural argument of the thesis: MWI is the only interpretation of quantum mechanics that is compatible with the Wheeler-DeWitt equation and that can derive the appearance of time — rather than postulating it. The following table summarises the comparison:

Interpretation	Treatment of time	Compatible with $\hat{H}\|\Psi\rangle=0$	Residual problem
Copenhagen	External classical time required	No — requires exterior observer	Circular: no exterior to the universe
Bohm (pilot wave)	Absolute Newtonian background time	No — requires privileged foliation	Violates Lorentz invariance; superdeterminism
Consistent histories	Time defined by consistent sets	Partially	Not derivable without Born rule; arbitrariness in set choice
MWI (Everett)	Time emerges via decoherence between branches	Yes — wave function is timeless and branching	Requires deriving Born rule; addressed in Ch.10 via holography

7.2.1 The Page-Wootters Mechanism as a Natural Consequence of MWI

In 1983, Don Page and William Wootters proposed a mechanism in which time emerges from the entanglement between a quantum 'clock' subsystem and the rest of the universe. The global state satisfies $\hat{H}|\Psi\rangle = 0$ (timeless), but internal observers perceive temporal evolution because they are entangled with the clock: measuring the clock's state conditions the rest of the universe into an evolving state.

This Page-Wootters mechanism is, in essence, a corollary of MWI applied to closed quantum systems. In MWI, each branch of the universal wave function contains a complete history from the perspective of internal observers, who perceive a coherent flow of time precisely because decoherence selects classically consistent branches. The appearance of temporal evolution is not fundamental but relational — it is the result of correlations between subsystems within each branch.

> *MWI's contribution to LQG: the Wheeler-DeWitt equation does not require an external time because MWI provides time internally. The branches of the universal wave function, differentiated by decoherence in the spin network (spin foam), generate the semiclassical time parameter that LQG needs to recover General Relativity as a low-energy limit. Without MWI, LQG requires an external reference time that its own formalism cannot supply — a fundamental incompleteness.*

7.2.2 The Arrow of Time as Irreversibility of Branching

The arrow of time is one of nature's great asymmetries: the laws of physics are symmetric under time reversal (CPT), yet experience and thermodynamics exhibit an irreversible temporal direction. LQG cannot derive this asymmetry from its timeless formalism. MWI offers a structural solution:

- The wave function of the universe evolves unitarily and reversibly according to the Schrödinger equation. There is no intrinsic temporal asymmetry in the dynamics.
- Decoherence with the environment produces an effectively irreversible branching: branches separate but do not recombine on macroscopic scales due to the vast number of environmental degrees of freedom.
- The irreversibility of branching — the practical inability to reverse complete decoherence — is the source of the arrow of time. Entropy grows because the number of branches accessible to an internal observer grows monotonically.
- In the context of LQG, the spin network in the past is 'simpler' (fewer nodes and links) than in the future. The branching of the wave function over the spin network encodes this asymmetry without any additional postulate.

This argument is impossible to reproduce within Copenhagen (which requires a pre-existing external classical time) or Bohmian mechanics (which postulates an absolute Newtonian time, making the arrow of time an assumption rather than a derived result). MWI is the unique interpretation for which the arrow of time is an output of the formalism rather than an input.

7.3 Deriving General Relativity from LQG + MWI

One of the most serious unresolved problems of LQG is the difficulty of recovering classical General Relativity in the low-curvature limit. The equations of Einstein must emerge as a semiclassical approximation of the spin network dynamics, but the mechanism is technically very demanding and conceptually obscure.

MWI's contribution at this point is indirect but essential. Decoherence between branches of the wave function defines which classical geometries are stable and persistent. The geometries that satisfy Einstein's equations are precisely those that survive decoherence because they are the ones that correlate consistently with matter states across all branches. Quantum geometries that do not satisfy Einstein's equations are destroyed by destructive interference between branches.

> *General Relativity is not an input of LQG but an output of the decoherence process that defines the classically stable branches of the wave function of the spin network. MWI is the mechanism by which LQG recovers classical physics. This reframes the semiclassical limit problem: it is not a problem of approximation but of selection — and MWI's decoherence is the selection mechanism.*

This argument can be formalised through the programme of 'emergent geometrodynamics': the classical geometry of spacetime is the geometry averaged over those branches of the wave function of the spin network that are mutually coherent. Decoherence eliminates superpositions of geometries and selects the observed classical geometry. The resulting programme unifies LQG (which provides the discrete quantum substrate) and MWI (which provides the emergence mechanism) into a coherent description of the classical world.

Chapter 8: Towards a Quantum Theory of Gravity and Discrete Spacetime

8.1 Main Candidates: Loop Quantum Gravity and String Theory

The search for a quantum theory of gravity has led to the development of several theoretical approaches, with loop quantum gravity (LQG) and string theory being two of the most prominent candidates.

Loop quantum gravity is an attempt to directly quantise gravity based on Einstein's geometric formulation of general relativity. In LQG, the fabric of space and time is considered to be composed of finite loops entangled in an extremely fine network called a spin lattice. The evolution of a spin lattice in time gives rise to a spin foam. A key feature of LQG is that it postulates that space and time are discrete at the Planck scale (approximately 10^{-35} metres), meaning that there exist indivisible fundamental units of volume and time. LQG is formally considered to be background-independent. One of its strengths is its treatment of singularities: the Big Bang is replaced with a 'Big Bounce', where a previous contraction phase is followed by an expansion phase. However, LQG is still under development and lacks direct experimental verification at accessible energies.

String theory addresses the unification of all fundamental forces, including gravity, by replacing the point particles of particle physics with one-dimensional objects called strings. Different vibration modes of these strings correspond to different particles, including the graviton. String theory requires the existence of extra spatial dimensions, typically ten in total, with six of them compactified at very small scales. While string theory has made significant advances in mathematical physics and provided insights into black hole physics and early cosmology, it faces challenges including the existence of a vast 'landscape' of possible universes (addressed in Chapter 9) and the lack of experimental verification at the required energy scales.

8.2 The Concept of Discrete Space-Time in Quantum Gravity

The idea that space and time might not be continuous but discrete at very small scales is a common feature that arises in various approaches to quantum gravity. In a continuous spacetime, one can divide any region of volume into smaller and smaller regions ad infinitum. A discrete spacetime posits that there exists a 'smallest possible volume' that is no longer divisible, and similarly a smallest 'unit of time' — a 'chronon' — beyond which time cannot be divided further.

In loop quantum gravity, the discretisation of spacetime arises naturally from the structure of spin lattices. The nodes of the spin lattice can be interpreted as volume quanta, and the links as area quanta. The size of these quanta is on the order of the Planck length cubed for volume and the Planck length squared for area. This implies that space itself has a granular structure at this fundamental scale, and that lengths, areas, and volumes are all quantised, taking only discrete values.

While string theory was originally formulated in a continuous space-time background, some research suggests that at the Planck scale, space-time might have an emergent and possibly discrete nature. The holographic principle, which arose from string theory, suggests that information contained in a volume of space can be encoded in a lower-dimensional boundary, which might imply that the dimensionality and continuity of space-time are illusory at a fundamental level.

One of the potential benefits of discrete spacetime is its ability to resolve singularities that appear in general relativity, such as the Big Bang singularity or the singularities inside black holes. If there is a minimum length and a minimum volume, then the density cannot become infinite. In loop quantum gravity, for example, the Big Bang is replaced by a Big Bounce, where the universe transitions from a contracting to an expanding phase, avoiding the singularity.

8.3 Integrating Quantum Gravity with a Discrete Space-Time Model

The integration of a quantum theory of gravity with a discrete space-time model in the context of quantum cosmology presents a formidable but potentially fruitful challenge. Loop quantum cosmology (LQC) has already made significant progress in applying LQG principles to cosmological models. LQC replaces the Big Bang singularity with a Big Bounce and provides a framework for studying the early evolution of the universe with discrete spacetime. In the context of LQC, the Wheeler-DeWitt equation is replaced by a difference equation reflecting the discrete nature of spacetime.

The integration of string theory with discrete spacetime and quantum cosmology is more complex. While string theory itself does not inherently postulate a discrete spacetime, the holographic principle suggests that the description of a volume of space can be encoded in a lower-dimensional boundary, which might imply an underlying discrete structure. The AdS/CFT correspondence — relating a theory of gravity in anti-de Sitter space to a conformal quantum field theory at its boundary — is a specific example, and its relationship to MWI is developed in Chapters 9 and 10.

An additional speculative proposal worthy of consideration postulates that the universe emerged from an initial singularity describable as a 'quantum space' with discrete properties of time and energy points — a lossless energy structure outside of time. While speculative, this proposal suggests another avenue in which discretisation could play a fundamental role in quantum cosmology, and its compatibility with the MWI = Multiverse hypothesis is a direction for future research.

Chapter 9: MWI and M-Theory: The Landscape as Branch Structure and the Emergent Bulk

9.1 The Landscape Problem in M-Theory

M-Theory and String Theory face a problem radically different from that of LQG but equally devastating: the overabundance of solutions. The vacuum of M-Theory is not unique. Compactifications of the extra dimensions admit an astronomically large number of stable configurations — estimated at 10^500 or more — each corresponding to a universe with different low-energy physics. This proliferation is known as the string landscape.

The problem has two aspects:

- Selection problem: why does our universe have the physical constants it has? The anthropic principle is the standard answer, but it is epistemic (we observe this universe because we are observers compatible with it) rather than ontological (it does not explain why this vacuum exists at all).
- Prediction problem: if all vacua exist, M-Theory cannot make predictions about the physical constants of our universe without a probability distribution over the landscape. The landscape measure is an open problem with no consensus solution.

9.2 MWI as an Ontological Selection Principle for the Landscape

MWI's contribution to the landscape problem is conceptually profound. The central idea is the following: the vacua of the string landscape are not separate universes in a metaphysical sense but branches of the universal wave function of the universe.

If the wave function of the universe evolves unitarily from an initial state — consistent with the Hartle-Hawking no-boundary proposal or a quantum initial singularity — then all landscape vacua accessible from that initial state appear as branches of the wave function, weighted by their squared amplitudes (Born rule).

> *This radically transforms the problem: the anthropic principle becomes unnecessary. Each landscape vacuum has a probability amplitude defined by the initial wave function of the universe. The question 'why this vacuum?' becomes 'what is the amplitude of this branch?' — a technical question within the MWI formalism, not an appeal to observers. The landscape measure is the Born measure over Hilbert space.*

This equivalence — landscape vacua = branches of the wave function — is the mathematical formulation of the MWI = Multiverse hypothesis in the context of M-Theory. The implications are far-reaching:

- The landscape measure is the Born measure over Hilbert space, not an additional measure imposed externally on the landscape.
- The distribution of physical constants across universes of the landscape is in principle predictable: determined by the amplitudes of the initial wave function of the universe, which depend on the dynamics of M-Theory at the Planck scale.
- The anthropic principle becomes a selection tool within a single quantum formalism, not an independent and philosophically questionable principle.

9.3 The Emergent Bulk: ER = EPR and MWI

Perhaps the most striking contribution that MWI can make to M-Theory concerns the emergence of the bulk. In the holographic formalism of AdS/CFT, the gravitational bulk emerges from the quantum field theory on the boundary. If the boundary theory is in a superposition of states — as naturally occurs in MWI — then the corresponding bulk is a superposition of geometries.

This picture is formalised by the ER = EPR conjecture (Maldacena and Susskind, 2013), which states that entangled particle pairs (EPR) are connected by quantum Einstein-Rosen wormholes (ER). Quantum entanglement and geometric connectivity are the same structure described in two languages. In the MWI context:

- Decoherence between branches of the wave function on the CFT boundary corresponds to the selection of a classical bulk geometry. Each coherent branch of the boundary wave function generates a different bulk geometry.
- Maximally entangled boundary states correspond to Einstein-Rosen wormhole seeds in the bulk: the very structure of MWI branches is what generates bulk connectivity.
- Destroying entanglement between two boundary regions (as happens when branches decohere completely) disconnects the corresponding bulk regions — spacetime 'tears'.
- The black hole information paradox is resolved because information is not lost in the bulk but is encoded in the quantum correlations of the boundary, corresponding to MWI branches.

> *Precise formulation: the AdS bulk is not a fundamental object but an emergent representation of quantum entanglement on the CFT boundary. MWI branches in the boundary theory correspond to distinct entanglement states, and therefore to distinct bulk geometries. The equation MWI = Multiverse, in the context of AdS/CFT, reads: distinct branches of the boundary wave function generate distinct cosmological universes (bulks). The 'It from Qubit' programme is the technical realisation of this statement.*

9.4 Comparative Assessment: What MWI Contributes That No Other Interpretation Can

Interpretation	Treatment of the landscape	Compatibility with holography	Problem in M-Theory
Copenhagen	Chooses a vacuum by collapse (who collapses the universe?)	Incompatible: no exterior observer	The universe has no external classical observer
Bohm	Single realised vacuum with hidden trajectories	Only superficially compatible	Cannot explain vacuum transitions; requires superdeterminism at cosmological scale
Consistent histories	Multiple histories without clear ontology	Partially compatible	Does not assign reality to unrealised vacua; arbitrary measure
MWI	All accessible vacua are real branches weighted by Born	Fully compatible: branches = CFT boundary states	Requires deriving Born rule — but holography provides it (Ch.10)

The case of Bohmian mechanics deserves special attention. Bohmian mechanics requires a single realised world with defined particle trajectories. In the cosmological context, this implies that the extra dimensions of M-Theory must be in a definite state, not in superposition. But the wave function of the early universe is inevitably a superposition of different compactifications. For Bohm to be consistent with M-Theory, it needs to postulate superdeterministic initial conditions that select a unique compactification from the outset — a highly restrictive and theory-unmotivated assumption that effectively reintroduces the very arbitrariness it was meant to avoid.

Chapter 10: The Holographic and Complementarity Principles in Quantum Gravity and Cosmology

10.1 The Holographic Principle: Information at the Boundary

The holographic principle is a property of string theories and a putative property of quantum gravity which states that the description of a volume of space can be thought of as encoded in a lower-dimensional boundary of the region, like a light horizon as a gravitational horizon. Originally proposed by Gerard 't Hooft, it was given a precise interpretation in string theory by Leonard Susskind, who combined his ideas with those of 't Hooft and Charles Thorn. In Susskind's formulation: the three-dimensional world of ordinary experience — the universe filled with galaxies, stars, planets, houses, rocks, and people — is a hologram, an image of reality encoded on a distant two-dimensional surface.

The holographic principle arose from black hole thermodynamics and the Bekenstein limit. The Bekenstein limit conjectures that the maximum entropy in any region scales with the square of the radius, rather than the cube as might be expected. In the case of a black hole, the information content of all objects that have fallen into the hole could be contained entirely in the surface fluctuations of the event horizon.

The prime example of holography is the AdS/CFT correspondence — a conjectured relationship between two types of physical theories. On one side are anti-de Sitter (AdS) spaces used in theories of quantum gravity, formulated in terms of string theory or M-theory. On the other are conformal field theories (CFTs), which are quantum field theories describing elementary particles. The AdS/CFT correspondence provides a non-perturbative formulation of string theory with certain boundary conditions and is the most successful realisation of the holographic principle, suggesting that a theory of gravity in (d+1)-dimensional space is equivalent to a quantum field theory in its d-dimensional boundary.

10.2 The Principle of Complementarity: Wave-Particle Duality at Cosmological Scales

Bohr's complementarity principle is a fundamental concept in quantum mechanics which holds that certain pairs of complementary properties — such as position and momentum, or wave and particle properties — cannot be observed or measured simultaneously in a single experiment. Bohr considered it one of the fundamental truths of quantum mechanics that setting up an

experiment to measure one quantity of a pair excludes the possibility of measuring the other, however an understanding of both experiments is necessary to characterise the object under investigation.

While the complementarity principle is traditionally discussed in the context of microscopic systems, its underlying principles concerning the limitations of our observation and the dual nature of reality offer new insights into cosmology. The idea of a 'gravitational complementarity principle' has been explored, suggesting that gravity has complementary dual features: the quantum and classical aspects of gravity are complementary and absolutely separated by the Planck length into Planckian and super-Planckian domains, respectively. In this scenario, Einstein's classical equations would be correct at a fundamental level in the super-Planckian domain, and quantum gravity would be entirely confined to the Planckian domain with a new type of very short-range interaction.

10.3 Emergence of Space-Time and the Born Rule from Holography and Complementarity

The holographic principle offers a potential framework for understanding the emergence of spacetime from a more fundamental, non-gravitational theory at the boundary. The geometry of spacetime in the bulk emerges from quantum degrees of freedom living on the lower-dimensional boundary. As discussed in Chapter 9, MWI branches in the boundary CFT generate distinct bulk geometries through the decoherence process — the MWI = Multiverse equation finds its technical implementation here.

The 'It from Qubit' programme, driven by researchers including Mark Van Raamsdonk, Netta Engelhardt, and Ahmed Almheiri, systematically explores how spacetime emerges from quantum entanglement. Its most important results relevant to this thesis are:

- Bulk geometry is encoded in the entanglement structure of the boundary. Destroying entanglement between two boundary regions disconnects the corresponding bulk regions.
- The Ryu-Takayanagi formula relates the entanglement entropy of a boundary region to the area of a minimal surface in the bulk — connecting quantum information (MWI branch structure) to geometry.
- The Engelhardt-Wall quantum extremal entropy formula extends this to include bulk quantum corrections, allowing recovery of the Page curve for evaporating black holes.
- The 'islands' formula (Penington; Almheiri, Mahajan, Maldacena, Zhao) resolves the black hole information paradox by identifying non-perturbative contributions to the gravitational path integral that correspond, in MWI language, to tunnelling between branches.

The Born rule — which describes the probabilistic nature of quantum mechanics — is also speculated to emerge as a holographic phenomenon. If the probabilities of MWI branches correspond to the squared norms of boundary CFT states, and if the boundary CFT state can be derived from the fundamental discrete level (Level 4), then the Born rule is not a postulate but a consequence of the entanglement structure of the quantum substrate. This is the programme of derivation advocated in this thesis as an alternative to the circular attempts within MWI alone.

> *In summary: the holographic principle is the formal connector between the ontological level (Level 4, quantum substrate) and the epistemological levels (Levels 1–3, the classical*

> *cosmological world). MWI is the branching structure that the holographic dictionary maps from the boundary to the bulk. Complementarity ensures that the quantum and classical descriptions are not simultaneously accessible — they are complementary aspects of the same ontological reality.*

Chapter 11: The MWI = Multiverse Hypothesis: Precise Formulation and Consistency Conditions

11.1 Two Versions of the Hypothesis

11.1.1 Weak Version (Epistemic Duality)

In its weak version, the hypothesis states that MWI branches and the universes of the cosmological multiverse (eternal inflation, cyclic LQC) are equivalent descriptions of the same set of possible histories of the universe, related by a change of perspective: the quantum perspective (universal wave function) vs. the classical-relativistic perspective (background spacetime).

This version is less ontologically committed but has empirical consequences: if correct, the cosmological predictions of the inflationary multiverse must be reproducible from the MWI formalism with the same initial wave function. The distributions of physical constants across 'bubble universes' must coincide with the Born probabilities of the corresponding branches.

11.1.2 Strong Version (Ontological Identity)

In its strong version, the hypothesis states that the universes of the cosmological multiverse are identical to the branches of the universal wave function. There are not two sets of universes (the quantum ones of MWI and the cosmological ones of inflation); there is a single set of quantum-geometric structures that appear as bubble universes from a classical perspective and as branches from a quantum perspective.

> *The strong version implies that the universal wave function (ontological Level 4) contains all the information of the cosmological multiverse, and that Tegmark's epistemological Levels 1, 2, and 3 are semiclassical approximations to different aspects of this wave function. The 'redundancy' of multiverses is not a problem to be solved but the expected signature of this deep equivalence.*

11.2 Consistency Conditions

For the hypothesis to be scientifically rigorous, the following conditions must be satisfied:

- Condition 1 — Measure equivalence: The Born measure over MWI branches must be demonstrably equivalent to the probability measure over bubble universes of eternal inflation (landscape measure). This requires an explicit mapping between the Hilbert space of quantum cosmology and the configuration space of inflation.

- Condition 2 — Derivation of the Born rule from holography: The Born rule cannot be postulated in the ontological version; it must be derived from the fundamental quantum level (Level 4) via the holographic formalism.
- Condition 3 — Semiclassical limit: The equations of General Relativity must be derivable as a semiclassical limit of the universal wave function through the MWI decoherence mechanism in LQG spin networks or M-Theory strings (as argued in Chapter 7).
- Condition 4 — Singularities as quantum boundary conditions: Big Bang and Big Crunch singularities must appear as boundary conditions of the quantum wave function, not as physical breakdown points. LQG with MWI replaces singularities with high-density quantum states from which time emerges coherently.
- Condition 5 — Interpretation-change invariance: Observable physics (CMB fluctuation spectrum, coupling constants, large-scale geometry) must be independent of whether the MWI perspective or the cosmological multiverse perspective is used. Only then are the two perspectives genuinely equivalent.

11.3 The Role of Closed Timelike Curves

The universal wave function with a Closed Timelike Curve (CTC) plays a specific role in the MWI = Multiverse hypothesis. A CTC in the wave function of the universe implies that the quantum state of the universe is self-predetermining: the boundary conditions of the past and future are mutually consistent and holistically determined.

In the context of MWI, a quantum CTC does not generate paradoxes because the wave function branches: instead of a single state that must be consistent with itself (generating grandfather-type paradoxes), there exist multiple branches each internally consistent. 'Circular causality' becomes 'self-consistency of the global wave function' — exactly what the Hartle-Hawking no-boundary proposal imposes.

The quantum CTC + MWI therefore generates a universe that is finite, edgeless, and apparently static from an external (ontological) point of view, but that contains an emergent arrow of time in each branch from an internal (epistemological) point of view. This structure makes the block universe model not a speculation but a formal consequence of taking MWI and the no-boundary proposal seriously.

Chapter 12: Alternative Interpretations: Bohmian Mechanics and the Quantum Multiverse

12.1 Bohmian Mechanics: A Theory of Hidden Variables

Bohmian mechanics, also known as pilot wave theory or de Broglie-Bohm theory, is an interpretation of quantum mechanics that postulates the existence of definite particle trajectories, guided by a wavefunction. In contrast to the Copenhagen interpretation, Bohmian mechanics provides a deterministic description of quantum phenomena without resorting to wavefunction collapse during measurement. A system of particles is described both by its wavefunction

(evolving according to the Schrödinger equation) and by the actual positions of the particles (evolving according to a guiding equation that depends on the wavefunction).

Bohmian mechanics solves the measurement problem by postulating that particles always have definite positions, even when they are not observed. The outcome of a quantum measurement is determined by the initial position of the particle and the evolution of the wavefunction. The probabilistic nature that we observe arises from our ignorance of the precise initial positions of the particles, which are assumed to be distributed according to the Born rule — not as a postulate but arising from a 'quantum equilibrium' condition on the initial distribution.

An important feature of Bohmian mechanics is its explicit nonlocality: the velocity of any particle depends on the wave function of the entire system, which in turn depends on the positions of all other particles, regardless of their separation.

12.2 Criticisms of Bohmian Mechanics: Nonlocality and Superdeterminism

Despite its ability to provide a realistic and deterministic interpretation of quantum mechanics, Bohmian mechanics faces several criticisms. The most fundamental is its explicit nonlocality. The instantaneous dependence of a particle's velocity on the positions of all other particles in the universe appears to conflict with the principles of special relativity. Relativistic formulations of Bohmian mechanics have been proposed, but they often require the introduction of a privileged foliation of spacetime, which appears to violate Lorentz invariance.

Bohmian mechanics has also been linked to superdeterminism — a potential loophole in Bell's theorem that would allow a local hidden variable theory to reproduce the predictions of quantum mechanics by postulating that choices of measurement setups are not statistically independent of the hidden variables. Some have suggested that Bohmian mechanics requires a form of superdeterminism to be consistent with all quantum phenomena, implying a lack of free will for experimenters.

A further significant criticism arises from Bohmian mechanics's apparent difficulty in providing a satisfactory account of the computational power of quantum computing. Unlike MWI, which finds a natural explanation for the efficiency of quantum algorithms in the superposition and parallel processing of multiple worlds, Bohmian mechanics — being a single-world theory — has difficulty explaining quantum computing power without explicitly invoking the superposition principle as a fundamental ontological element.

12.3 Bohmian Mechanics as Many Worlds in Denial

Some have argued that Bohmian mechanics could be considered a 'many worlds in denial' theory. In Bohmian mechanics, the wavefunction of the universe contains information about all possible particle configurations, and the branches of the wavefunction that do not contain the actual particle configuration still influence the motion of the particles through the quantum potential. These 'empty branches' or 'empty worlds' do not contain particles, but are part of the universal wavefunction and play a role in the dynamics of the 'real' world.

In relation to the proposed model of the quantum multiverse, Bohmian mechanics faces a fundamental difficulty: most of today's major theoretical frameworks — cyclic cosmology,

inflationary cosmology, string theory, and loop quantum gravity — tend to favour or even imply the existence of a multiverse as a natural consequence of their fundamental principles. Bohmian mechanics, with its commitment to a single objective reality and a single evolving universe, stands as an exception to this dominant tendency. Its empty branches cannot serve as the epistemological levels of the proposed classification, because they are not different perspectives on a fundamentally multiple reality but mere phantoms of a fundamentally single one.

12.4 Probabilities in Bohmian Mechanics versus MWI

A final and fundamental difference concerns the treatment of objective probabilities. MWI is distinguished by its attempt to provide an ontological basis for the probabilities we observe in quantum mechanics, linking them to the existence measure or weight of each branch. In contrast, Bohmian mechanics — like the Copenhagen interpretation — generally assumes the validity of the Born rule without offering a fundamental ontological explanation of why quantum probabilities have the values they do.

While Bohmian mechanics provides deterministic trajectories for particles, their initial distribution and the shape of the wavefunction that guides them are assumed to conform to the Born rule, thus incorporating probability without explaining its ontological origin. This is precisely the problem that the holographic derivation of the Born rule (proposed in Chapter 10) would solve for MWI, giving MWI a decisive advantage over Bohmian mechanics on the question of probability.

Chapter 13: Synthesis and the Proposed Model of the Quantum Multiverse

13.1 Hierarchical Structure of the Proposed Model

The quantum multiverse model proposed in this thesis is based on the distinction between epistemological and ontological levels. The first three levels are conceived as epistemological — related to our way of knowing or accessing the possibility of other universes — while the fourth level represents the ontological form of the universe itself. The full model, integrating the contributions from quantum cosmology, MWI, holography, LQG and M-Theory, has the following hierarchical structure:

Level	Description	Nature	Associated Theory	MWI's Contribution
0 (Planck)	Discrete spacetime; spin network or strings	Primary ontological	LQG / M-Theory	Defines the Hilbert space over which the universal wave function acts
1 (Quantum)	Universal wave function; superposition of geometries and fields	Secondary ontological	Quantum cosmology; WdW equation	MWI = branch structure; time and arrow of time emerge by

Level	Description	Nature	Associated Theory	MWI's Contribution
				decoherence
2 (Semiclassical)	Classical background geometries; General Relativity emerges	Primary epistemological	General Relativity; LQC	Decoherence selects classically stable branches; GR is an output, not an input
3 (Cosmological)	Bubble universes; string landscape; cyclic models	Secondary epistemological	Eternal inflation; ekpyrotic models	'Universes' are branches of the wave function seen from a classical perspective
4 (Observable)	Observable universe; physical constants; CMB	Tertiary epistemological	Standard physics; observational cosmology	Probability of observing these constants = Born amplitude of the branch

13.2 The Role of Holography as Connector

Holography functions as the formal connector between Levels 0–1 (ontological) and Levels 2–4 (epistemological). Its function is twofold:

- Bottom-up: encodes the quantum information of Level 0 (spin network, strings) on a lower-dimensional boundary. MWI branches on the boundary correspond to different bulk geometries. The observable universe (Level 4) is the holographic image of the fundamental quantum state.
- Top-down: allows probabilities (Born rule) and the arrow of time (asymmetry of entanglement) to be derived from the quantum level, without postulating them. The Born rule emerges from the entanglement structure of the CFT boundary.

This dual function transforms the MWI = Multiverse hypothesis from an interpretive statement into a technical one: if holography is correct, MWI and the cosmological multiverse are dual in the technical sense of AdS/CFT.

13.3 Summary of MWI's Structural Contributions

Irreducible problem	Affected theory	MWI's structural solution	Why other interpretations fail
Problem of time $(\hat{H}\|\Psi\rangle = 0$ without external time)	LQG / Quantum cosmology	Time emerges from decoherence between branches; Page-Wootters mechanism is a consequence of MWI	Copenhagen needs external classical time; Bohm postulates absolute time; both are circular
Arrow of time without temporal asymmetry in the laws	LQG / Quantum thermodynamics	Irreversible branching by decoherence; entropy = number of accessible branches	Other interpretations take the arrow of time as an external assumption

Irreducible problem	Affected theory	MWI's structural solution	Why other interpretations fail
Semiclassical limit: deriving GR from LQG	LQG	Decoherence selects branches with classical geometry satisfying Einstein's equations	Without MWI, selecting the classical geometry requires an additional unfounded principle
Selection principle for the string landscape	M-Theory / Strings	Landscape vacua = Born-weighted branches of the wave function	Copenhagen cannot grant reality to unrealised vacua; Bohm requires superdeterminism
Bulk as emergent in AdS/CFT	M-Theory / Holography	MWI branches on the CFT boundary generate distinct bulk geometries; decoherence crystallises the bulk	Without branch superposition, no mechanism generates a superposition of bulk geometries
Ontological derivation of the Born rule	Quantum mechanics / MWI	Emerges from entanglement structure on the holographic boundary via the It from Qubit programme	Copenhagen postulates it; Bohm assumes it in initial conditions; both are ad hoc

Chapter 14: Priority Research Lines

14.1 For the Core of the Thesis

Based on the foregoing analysis, the following research lines are priorities for developing the doctoral thesis in a way that renders the MWI = Multiverse hypothesis technically robust:

- Formalise the Page-Wootters mechanism in the context of LQC (Loop Quantum Cosmology): demonstrate that the semiclassical time that LQC needs to recover classical cosmological dynamics emerges naturally from the entanglement between subsystems within the wave function of the spin network. This is the most immediate and technically tractable priority.
- Mapping between the Born measure in MWI and the landscape measure in M-Theory: seek an explicit mapping between the amplitudes of the initial cosmological wave function and the transition probabilities between string landscape vacua, working in the WKB limit of the Hartle-Hawking wave function.
- Explore the ER = EPR conjecture in the MWI context: if entangled pairs of MWI branches are connected by Einstein-Rosen wormholes, this would provide the geometric mechanism by which the bulk emerges from branch entanglement. This line connects directly with the 'It from Qubit' programme.
- Derive the Born rule from holography in the context of the universal wave function with a CTC: explore whether the self-consistency of the wave function under the CTC imposes the Born rule as the only internally coherent probability distribution.
- Investigate the compatibility of discrete spacetime (Level 0) with the branching structure of MWI: does the discrete structure of the spin network impose constraints on which

branches can decohere classically? This could provide a natural ultraviolet cutoff on the branch space.

14.2 Connections with Recent Research

The following recent developments in the literature are especially relevant for the thesis and must be incorporated:

- The work of Aron Wall and collaborators on quantum extremal entropy in AdS/CFT (Engelhardt-Wall formula): provides a precise formulation of how bulk singularities are related to boundary entanglement, relevant to the derivation of the Born rule.
- The 'islands' programme in the black hole information paradox (Penington; Almheiri, Mahajan, Maldacena, Zhao): shows that information is recovered through non-perturbative effects of the wave function consistent with MWI's unitary evolution.
- Jackiw-Teitelboim (JT) gravity as a toy model of AdS2/CFT1: allows exact calculation of the gravitational partition function, which in the MWI interpretation corresponds to the sum over all geometries (all branches).
- The Ryu-Takayanagi formula and its quantum generalisations: minimum-area surfaces in the bulk correspond to entanglement entropy on the boundary, which in MWI corresponds to the 'surface' separating branches — the geometric face of decoherence.
- Progress in loop quantum cosmology on the resolution of the Big Bounce: recent numerical results in LQC provide concrete evidence for quantum transitions through the classical singularity, offering a testing ground for the Page-Wootters mechanism in this context.

Chapter 15: Conclusions

This doctoral thesis has developed a detailed framework for understanding the quantum multiverse, integrating concepts from quantum cosmology, interpretations of quantum mechanics, and theories of quantum gravity. The proposed model, with its distinction between epistemological levels and an ontological level based on discrete space-time, offers a new perspective on the nature of the multiverse and opens avenues for future research in this fundamental field of theoretical physics.

The central argument can be stated as follows. Contemporary physics suffers from a structural redundancy: MWI, eternal inflation, cyclic models, and the string landscape all generate multiverses that appear to describe the same set of possible universes in different languages. This redundancy is not merely an aesthetic problem — it is a signal of an underlying equivalence that a complete quantum theory of gravity must make exact and derivable.

The thesis argues that the Many-Worlds Interpretation is the key element that makes this unification possible, and that its role is not interpretive but structural. The asymmetric contributions are the following:

In Loop Quantum Gravity: MWI resolves the problem of time by providing the internal mechanism — decoherence between branches — by which semiclassical time emerges from the Wheeler-DeWitt equation. It also provides the mechanism by which the arrow of time emerges

without postulating it, and the mechanism by which General Relativity is selected from the space of quantum geometries. No other interpretation can do this without circularity or ad hoc assumptions.

In M-Theory: MWI transforms the landscape problem from a problem of anthropic selection into a problem of quantum amplitudes. Landscape vacua are branches of the universal wave function, and the Born rule provides the probability measure without additional principles. Through ER = EPR and holography, MWI branches in the boundary theory generate bulk geometries, resolving the problem of how the bulk emerges from quantum entanglement.

The MWI = Cosmological Multiverse hypothesis: in its strong version, states that the universes of the cosmological multiverse are identical to the branches of the universal wave function. The four-level classification proposed in this thesis — three epistemological levels and one ontological level — maps precisely onto this equivalence: the epistemological levels are different classical-relativistic perspectives on the same universal wave function; the ontological level is the wave function itself.

The thesis has also argued that Bohmian mechanics, while an intellectually serious alternative, cannot play the structural role that MWI can in quantum gravity. Its commitment to a single objective reality requires superdeterministic initial conditions in the cosmological context, and its 'empty branches' cannot serve as the epistemological levels of the proposed classification.

The block universe model — a static four-dimensional block in which all moments coexist — emerges naturally from the combination of MWI and the no-boundary proposal with a closed timelike curve. The universe is finite, edgeless, and ontologically static, but each internal observer branch perceives an irreversible temporal evolution generated by decoherence. This resolves the apparent tension between the timeless character of the fundamental equations and the manifest directionality of our experience.

> *The final quantum theory of gravity cannot limit itself to unifying LQG or M-Theory with standard quantum mechanics. It must incorporate MWI as the emergence mechanism of the classical world from the quantum-gravitational substrate. The MWI = Cosmological Multiverse hypothesis is the statement that, when this is achieved, it will be discovered that the multiple languages of the multiverse — quantum, inflationary, cyclic, from the landscape — were all descriptions of the same mathematical object: the universal wave function of the universe, evaluated from different epistemological perspectives.*

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